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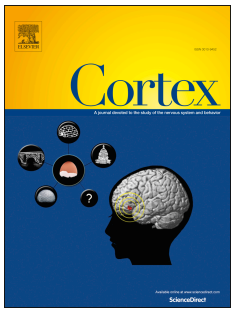

Rest on it: Awake quiescence facilities insight

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Rest on it: Awake quiescence facilities insight

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Abstract

Many scientific discoveries have been explained by a sudden gaining of insight with regards to an ongoing problem. Insight is characterised by a mental restructuring of acquired information, from which new explicit knowledge can be drawn, leading to qualitative changes in behaviour. Extended sleep facilitates the gaining of insight, possibly because it is conducive to the stabilisation and restructuring of new memory representations via consolidation. Research shows that a brief period of awake quiescence (quiet resting), too, can support consolidation: people remember more new memories if they quietly rest for several minutes after encoding than if they engage in a task involving ongoing sensory input after encoding. However, it remains unknown whether awake quiescence inspires insight. Using a number-based problem-solving task (the Number Reduction Task – 'NRT'), we reveal that, like sleep, awake quiescence facilitates the rapid gaining of insight: young adults were more than twice as likely to demonstrate new explicit knowledge of a hidden solution to the NRT if initial exposure to this task was followed by 10 minutes of awake quiescence than an unrelated perceptual task. These findings indicate that, at least for the NRT, the development of insight is not restricted to sleep but can be achieved via a brief period of awake quiescence. Thus, contrary to conventional wisdom and theories, when faced with a novel problem we may not always need to 'sleep on it' to find a novel solution, simply 'resting on it' may be enough.

Key words

Consolidation; Memory; Problem solving; Number Reduction Task.

Introduction

"Eureka!" - a solution is born. When faced with a new problem, it often appears that there is no apparent, or at least obvious, solution in sight or mind. However, after several minutes or days, the sudden manifestation of a solution in consciousness can occur. This "eureka!" moment reflects the abrupt gain of new explicit knowledge that leads to qualitative changes in behaviour, often allowing us to solve a problem more efficiently. Such qualitative changes in behaviour are believed to signify the mental restructuring of acquired information, from which new explicit knowledge can be drawn (Wagner, Gais, Haider, Verleger, & Born, 2004). Behaviourally, this is characterised by a sudden transition from a state of not knowing to a state of knowing, which changes how we interact with the problem at hand (Hélie & Sun, 2010; Verleger et al., 2013). Extensive research demonstrates the sudden development of insight in a variety of problem-solving tasks (e.g. for review see Sio & Ormerod, 2009; Verleger et al., 2013). However, the specific neurocognitive mechanisms of insight, especially during wakefulness, are ill-defined and under-researched. This paper reports a study investigating the conditions that influence the development of insight within the context of wakeful

memory consolidation, i.e. the early stabilisation and reorganisation of memories in the awake state (Dudai, 2004; Wixted, 2004).

In order to examine insight, a task is required that can provide an objective and reproducible measure (Verleger et al., 2013). The Number Reduction Task (NRT; e.g. Rose et al., 2002; Wagner et al., 2004) permits experimenters to determine the time point when insight occurs, that is, when new explicit knowledge of a hidden abstract rule is gained and applied to the problem at hand. In the NRT, this is demonstrated as an abrupt, qualitative shift in how participants respond. In each NRT trial (see Figure 1b), participants are asked to transform a given string of eight digits into a new 'solution string' of 7 digits through the stepwise digit-by-digit application of two simple rules, which are provided by the experimenter. This is done until the participant computes the 7th (final) digit in the solution string. The computation of this 7th digit is the required solution to each NRT trial. As a result, participants are required to respond with the correct 'solution digit' before moving to a subsequent trial. In this task, with increasing practice of applying the two given rules to strings of digits, participants' responses become gradually faster over time before reaching a plateau (Tan, Zou, Chen, & Luo, 2015; Wagner et al., 2004; Yordanova et al., 2008; Yordanova, Kolev, Wagner, & Verleger, 2009). However, a hidden rule - where the 2nd digit in the solution string is always the same as the 7th (final) digit in the string - is implemented, but not communicated to participants, and is therefore initially processed at an implicit level without conscious awareness. If discovered, this hidden rule enables the participant to find the 7th digit of the solution string much quicker than when working through the solution string via the two given rules. As a result, the time point when a participant gains insight into the hidden rule can be determined precisely by (i) a sudden reduction in the number of digits computed in the solution string, which corresponds with (ii) a steep decrease in the time that it takes participants to correctly respond to trials. The NRT has proven to be robust tool in the investigation of insight, and is sensitive to various experimental manipulations, including sleep (Darsaud et al., 2011; Rose et al., 2002; Wagner et al., 2004; Yordanova et al., 2008; Yordanova, Kolev, Wagner, Born, & Verleger, 2012; Yordanova et al., 2009).

Research has shown that an extended period of sleep facilitates the development of insight in the NRT (Darsaud et al., 2011; Rose et al., 2002; Wagner et al., 2004; Yordanova et al., 2008, 2012). In these studies people were typically more than twice as likely to discover the hidden rule if initial exposure to the NRT was followed by an extended (~4-8 hours) period of sleep than by an equally long period of active wakefulness (e.g. going about their daily activities). Wagner et al. (2004) hypothesised that sleep facilitates the development of insight because it is conducive to the reorganisation of new task-related memory representations via consolidation.

Consolidation refers to the automatic neural process by which new memory representations are stabilised and reorganised (Dudai, 2004; Wixted, 2004). In keeping with Wagner et al.'s (2004) hypothesis, extensive research demonstrates that sleep, relative to a period of filled wakefulness, is conducive to the consolidation of a variety of memory types, including those pertaining to new spatial (e.g. Ferrara et al., 2008; Wamsley et al., 2010), verbal (e.g. Clemens et al., 2005; Lahl et al., 2008), motor (e.g. Walker et al., 2003; Backhaus and Junghanns, 2006), and linguistic (e.g. Warker and Dell, 2006; Dumay and Gaskell, 2007; Tamminen et al., 2010; Gaskell et al., 2014) information. It is hypothesised that sleep supports consolidation because it provides a state of reduced sensory input and ongoing task engagement, which is conducive to opportunistic consolidation (Mednick, Cai, Shuman, Anagnostaras, & Wixted, 2011; Wixted, 2004). In particular, sleep has been shown to facilitate the spontaneous offline replay of neural activity associated with recently encoded memory representations in rodents (Ji & Wilson, 2007; Peyrache, Khamassi, Benchenane, Wiener, & Battaglia, 2009; Wilson & McNaughton, 1994) and, more recently, humans (Cairney, Guttesen, El Marj, & Staresina, 2018; Schönauer et al., 2017). The offline replay of recently encoded memory representations appears to be an important underlying mechanism of consolidation (Lewis & Durrant, 2011; Ramadan, Eschenko, & Sara, 2009; Wamsley, 2014). The role of replay in consolidation is evidenced by (i) a positive correlation between the degree of replay and subsequent

memory in humans and rodents (Carr, Jadhav, & Frank, 2011; Deuker et al., 2013; Foster & Wilson, 2006; Karlsson & Frank, 2009; Tambini, Ketz, & Davachi, 2010), and (ii) poor subsequent memory in rodents following electrophysiological disruption of neural replay (Ego-Stengel & Wilson, 2011). Moreover, using the NRT, it has been shown that specific patterns of neural activity (e.g. increased alpha activity, 8-12Hz) during slow wave sleep (SWS) are predictive of whether a person subsequently gains insight (Darsaud et al., 2011; Yordanova et al., 2008, 2012, 2009). It is proposed that these patterns of activity are related to the consolidation of new representations pertaining to the NRT which facilitate the gaining of insight (Verleger et al., 2013; Wagner et al., 2004; Yordanova et al., 2009).

Importantly, recent research in humans and rodents has demonstrated that replay is not restricted to sleep, but also occurs during wakefulness, especially awake quiescence (Carr et al., 2011; Deuker et al., 2013; Karlsson & Frank, 2009; Tambini et al., 2010). In keeping with this finding, behavioural research in humans has shown that awake quiescence (resting wakefulness under strict conditions of minimal sensory input and cognitive engagement), relative to active wakefulness (ongoing sensory input via an unrelated perceptual task), facilitates the consolidation of recently acquired memories (Craig & Dewar, 2018; Craig, Dewar, Della Sala, & Wolbers, 2015; Craig, Sala, Dewar, Della Sala, & Dewar, 2014; Craig, Dewar, Harris, Della Sala, & Wolbers, 2016; Dewar, Alber, Butler, Cowan, & Della Sala, 2012; Dewar, Alber, Cowan, & Della Sala, 2014; Dewar, Cowan, & Della Sala, 2007). Like sleep, awake quiescence is hypothesised to be conducive to opportunistic consolidation (Mednick et al., 2011; Wixted, 2004) because it provides a state of reduced sensory input and cognitive engagement that promotes the neural replay of new memory representations (Craig et al., 2015; Craig, Dewar, et al., 2016; Dewar, Alber, et al., 2012; Dewar et al., 2014). These findings suggest that, like sleep, awake quiescence could facilitate the gaining of insight.

Previous research certainly indicates that the development of insight is not restricted to sleep but can also be achieved during wakefulness (e.g. Wagner et al., 2004; Tan et al., 2015). In particular, people are more likely to gain insight into a problem if, following initial exposure, they (even briefly) remove themselves from the problem and engage in a different activity before subsequently returning to it, rather than if they continuously focus on the problem in a single session (Dodds, Ward, & Smith, 2004; Hélie & Sun, 2010; Segal, 2004; Tan et al., 2015). This phenomenon is often referred to as the 'incubation' effect (for review see Sio and Ormerod, 2009). The most prominent theories accounting for the incubation effect can be roughly divided into two broad categories of conscious and unconscious processes (Sio & Ormerod, 2009). Conscious processes include the attention-withdrawal hypothesis (Segal, 2004), which posits that the incubation effect is due to a switch in attention from an ongoing problem to task-unrelated materials, which 'refreshes' the ability to apply an efficient strategy when returning to the problem. It has also been suggested that a reduction in cognitive fatigue during the incubation period can account for the effect (Posner, 1973). In contrast, theories of unconscious processes suggest that during the incubation period there is a gradual (unconscious) transformation of information which results in an increased likelihood of new explicit knowledge being developed, i.e. insight (Sio & Ormerod, 2009).

The consolidation hypothesis of insight (Lewis & Durrant, 2011; Wagner et al., 2004; Yordanova et al., 2012, 2009) builds on these theories of unconscious processing by proposing a specific neurocognitive basis of insight, i.e. consolidation. In keeping with this hypothesis, there have been a few hints toward consolidation being responsible for the wakeful incubation effect. For example, it has been reported that long incubation periods are more beneficial than short incubation periods (Dodds et al., 2004), which could reflect the consolidation and reorganisation of new information over time (Dudai, 2012; Mednick et al., 2011; Wixted, 2004). Also, although results have been mixed, a cross-study comparison suggests that the magnitude of the incubation effect might be affected by the level of cognitive demand during the incubation period (for review see Sio & Ormerod, 2009). Given that minimal task demand/sensory input benefits the consolidation of new memories (Craig et al., 2015, 2014; Craig, Dewar, et al., 2016; Dewar, Alber, et al., 2012; Dewar et al., 2014, 2007), this

incubation effect finding could reflect differential effects of task demand/sensory input on memory consolidation. However, to the best of our knowledge, no study has directly compared the effects of incubation periods of quiet rest vs. task performance/ongoing sensory input in gaining insight. Some studies have used incubation periods comprising 'rest' (e.g. Smith and Blankenship, 1989). However, it is unclear whether such rest periods were devoid of sensory input and cognitive engagement as in the aforementioned memory consolidation research, which reports a benefit of post-encoding awake quiescence (Craig, Wolbers, et al., 2016; Craig & Dewar, 2018; Craig et al., 2015; Craig, Dewar, et al., 2016; Dewar, Alber, et al., 2012; Dewar et al., 2014, 2007).

Therefore, it remains unclear whether the wakeful incubation effect is boosted via awake quiescence, relative to other wakeful activities (e.g. active wakefulness involving ongoing sensory input), as predicted by consolidation theory. In the study reported here, we addressed this question directly by combining our established consolidation paradigm with the NRT. Young adults were first trained on two blocks of 30 NRT trials (total = 60 NRT training trials) to induce mental representations of the task that remained implicit with regard to the hidden rule. The training period was followed by one of two 10-minute delay conditions, where participants experienced either: (i) awake quiescence (quiet resting under strict conditions of minimal sensory input and cognitive engagement) or (ii) an unrelated perceptual task (ongoing sensory input via a spot the difference game; Dewar, Alber, et al., 2012). Following the 10-minute delay period, all participants were tested on a maximum of 10 further NRT blocks, each containing 30 trials, until they demonstrated insight, i.e. applied new explicit knowledge of the hidden rule, for 2 full blocks (60 NRT trials). Those who did not gain insight were requested to complete all 10 post-delay condition blocks (300 NRT trials). Each block of 30 NRT trials was followed by a short break (10 seconds). If consolidation explains, at least some of, the wakeful incubation effect, then, a wakeful incubation period comprising awake quiescence should be more conducive to the development of insight than an unrelated perceptual task.

Methods

Sixty young adults (31M:29F; Mean age = 22.19 years, SD = 3.40) were recruited as participants. They were pseudo-randomly allocated to one of two 10-min delay condition groups (quiescence (N = 30) or perceptual task (N = 30)) prior to the experiment. All participants provided their written informed consent prior to the onset of the study. The experimental procedure took place in a single session and was broken into three key phases: (1) Training, (2) 10min delay, and (3) Testing. Figure 1 provides an overview of the procedure and the Number Reduction Task (NRT).

<<INSERT FIGURE 1 ABOUT HERE>>

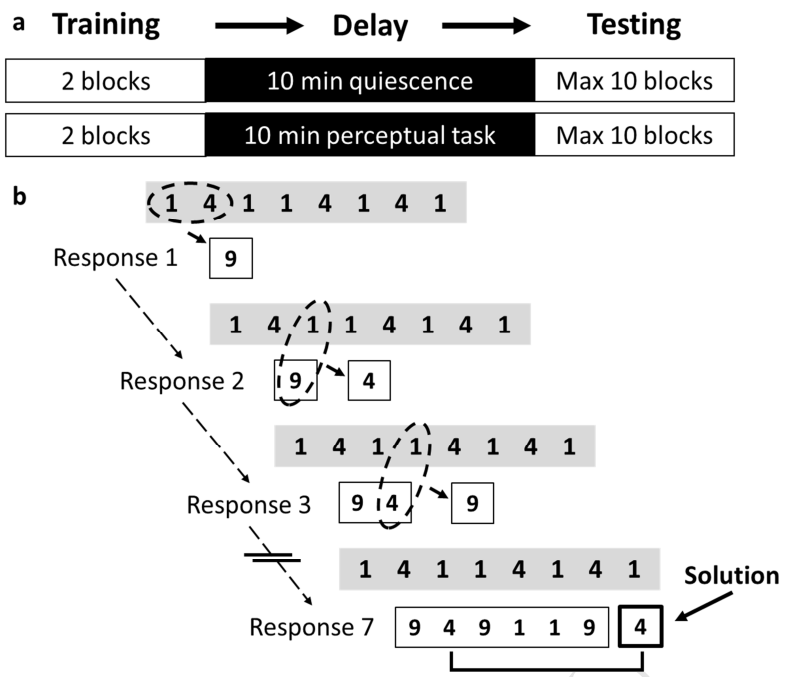

Figure 1. (a) Overview of the experimental procedure and **(b)** an example of a Number Reduction Task (NRT) trial showing the learned rules and the hidden rule, i.e. the solution digit always equals the 2nd response (adapted from Wagner et al. 2004) – see Methods for specific details. All participants completed 2 blocks of 30 NRT trials during the pre-delay condition training phase. They then experienced 10 minutes of either (i) awake quiescence (quiet rest under strict conditions of minimal sensory input) or (ii) an unrelated perceptual task (a visual spot-the-difference game). After the delay phase, all participants completed the final part of the procedure, the testing phase, where a maximum of 10 blocks of 30 NRT trials were presented (maximum number of post-delay condition trials = 300).

Participants first learned the 'same' and 'different' rules of the Number Reduction Task (NRT) via a pen and paper version of the NRT (5 trials) which did not contain the hidden rule. In each NRT trial, a participant was presented a different string of eight digits, composed of only '1', '4', and '9'. For each string of digits, the participant was required to determine a digit defined as the 'solution' of the trial. Finding this solution digit could be achieved by sequentially processing the digits pairwise from left to right while adhering to two simple rules: (i) same rule – when the result of two identical digits is the same digit as the two being compared (i.e. '1' and '1' yields a response of '1', '4' and '4' yields a response of '4', '9' and '9' yields a response of '9'), and (ii) different rule – when the result of two non-identical digits is the remaining third digit of this three-digit system (e.g. '1' and '4' yields a response of '9', '1' and '9' yields a response of '4', '4' and '9' yields a response of '1'). After the first response, comparisons had to be made between the preceding result and the next digit in the presented string (see Figure 1). The seventh response was the final solution to the trial, which was required before moving to the next trial. Participants were only told that the solution digit was to be determined and this could be done at any time. As in previous work (e.g. Wagner et al., 2004), participants were not informed that presented digit strings within the main experimental trials were generated in such a way that the last three (5th, 6th and 7th) responses always mirrored the previous three (2nd, 3rd and 4th) responses or that the 2nd digit in a response string always equalled the 7th digit, i.e. the hidden rule, (see example response sequence next to 'Response 7' in Figure 1).

They then completed a block of 10 practice trials in the computerised version of the task, which was programmed and run using Psychopy (Peirce, 2008). These computerised practice trials were identical to the initial pen and paper trials, but digit sequences were presented on a computer screen, and participants were asked to use a computer keyboard number pad to enter their responses, which appeared as digits on the screen. Once participants had 'solved' a trial, they were required to submit their solution by clicking either '1', '4' or '9' which was found at the bottom of the computer screen. The task would then move to the next trial. Only one trial was presented on the computer screen at any one time. None of these practice trials contained the hidden rule. Following the successful completion of the computerised practice trials, and confirmation from the participant that they understood what was being asked of them, all participants entered the NRT training phase. Previous work using the NRT has utilised 3 blocks during training (total = 90 trials) (e.g. Wagner et al., 2004). However, pilot work for the current study suggested that two blocks of trials (total = 60 trials) provided sufficient exposure to the NRT to generate new representations that could result in subsequent insight, without providing excessive exposure that would increase the likelihood of insight being gained during training. All 60 trials in the training phase contained the hidden rule, thus permitting potential implicit acquisition of this information prior to the delay phase. To minimise the possibility of participants thinking intentionally about the NRT during the delay phase, participants were not informed that they would be asked to complete further NRT trials later in the experiment.

Following the training phase, participants entered the delay phase, where they experienced 10 minutes of either: (i) awake quiescence (quietly rest under strict conditions of reduced sensory stimulation in a dimly lit room), or (ii) an engaging unrelated perceptual task (computerised visual spot-the-difference game; Craig et al., 2015; Craig, Dewar, et al., 2016; Dewar, Alber, et al., 2012). Participants assigned to the *awake quiescence* condition were asked to sit quietly in the dimly-lit testing room and relax while the experimenter left the room to "set up the next section of the experiment" (Craig & Dewar, 2018; Dewar, Alber, et al., 2012). Care was taken to ensure that the testing room was devoid of any rich visual and/or audible sensory cues to minimise sensory information. Participants assigned to the *perceptual task* group were asked to play a visual spot the difference game (Dewar, Alber, et al., 2012). Participants performed a total of 30 spot-the-difference trials in silence, each 20 second in duration. A trial consisted of the presentation of a pair of real-world photos on the computer screen (see Supplementary information for examples). Photos were identical other than for two discrete differences. Participants were instructed to search for these two differences, and to silently point toward them if discovered. The experimenter sat behind the participant during this task and scored the number of differences that the participant correctly identified.

After the delay phase, all participants completed the final part of the procedure, the testing phase, where a maximum of 10 blocks of 30 NRT trials were presented (maximum number of post-delay condition trials = 300). As in previous work using the NRT (Darsaud et al., 2011; Debarnot, Rossi, Faraguna, Schwartz, & Sebastiani, 2017; Rose et al., 2002; Wagner et al., 2004; Yordanova et al., 2008, 2012), gaining insight into the hidden rule was defined as (i) a sudden reduction in the number of digits computed in the solution string, which corresponds with (ii) a steep decrease in the time that it takes participants to correctly respond to trials. Once the participant had demonstrated this behaviour for 2 blocks (total = 60 trials), the experimenter stopped the task. Those who did not demonstrate insight were required to complete the full 10 blocks of NRT trials.

For NRT trials performed during the training and testing sessions, we examined (i) whether participants provided a correct solution digit (1, 4, or 9) in each trial, (ii) the point at which they stopped using the full 7-digit string to provide a solution, and (ii) the time that it took participants to respond to each trial. From these data we calculated the percentage of correct NRT responses during the training and testing phases of the procedure. We also calculated mean response times for each block of NRT trials during these two phases. These data were used to examine the gaining of

insight into the hidden rule, as demonstrated by (1) a sudden reduction in the number of digits computed in the solution string, and (2) a steep decrease in the time that it takes participants to correctly respond to trials (Wagner et al., 2004). From these data we extracted whether participants had gained insight, i.e. showed evidence of a non-taught solution that allowed more efficient NRT performance.

Data from two participants (quiescence group) were lost because we experienced a computer-related problem for one participant, and a second participant did not complete the full procedure. Thus, the following analyses report data from 58 participants (quiescence group: N=28, perceptual task group: N = 30).

Results

The two groups were well matched in their background and their performance on the practice trials (see supplementary information).

NRT training phase (60 trials). During training, all participants completed 60 NRT trials which included the hidden rule. There was no significant between-group difference in the percentage of correct trials during training (quiescence group: mean = 96.96% correct, SD = 3.33%; task group: mean = 95.89% correct, SD = 4.71%; $F(1,56) = 0.994$, $p = .323$, $\eta\rho^2 = .017$). The mean time that it took participants to complete training trials was also matched across groups (quiescence group: mean = 17.82 seconds, SD = 4.34 seconds; task group: mean = 16.25 seconds, SD = 3.58 seconds; $F(1,56) = 2.267$, $p = .138$, $\eta\rho^2 = .039$). Therefore, the mean time that it took participants to complete training phase trials was 17.82 minutes (SD = 4.34 minutes) in the quiescence group and 16.25 minutes (SD = 3.58) in the task group.

Given that training phase NRT trials included the hidden rule, it was possible that participants could develop insight (discover the hidden rule that enabled more efficient performance) and apply it to NRT training trials. Indeed, as in previous work (Wagner et al., 2004), a minority of participants demonstrated insight during training. Figure 2 shows the percentage of participants who gained insight during training. There was no significant between-group difference in the percentage of participants who gained insight during this phase of the experiment (total = 7/58, quiescence group = 4/28, task group = 3/30; Fisher exact test $p = .701$). Participants who gained insight in the training phase were not included in the testing phase data and analyses.

Post-delay phase NRT performance

NRT testing phase (max 300 trials). As during training, there was no significant between-group difference in the percentage of correct trials during testing (quiescence group: mean = 95.89%, SD = 6.60%; task group: mean = 96.87%, SD = 2.32%; $F(1,56) = 0.591$, $p = .445$, $\eta\rho^2 = .010$). Performance was consistent across blocks, where, even in the final (10^{th}) block of trials, participants in the quiescence and perceptual task groups who had not gained insight performed correctly on more than 90% of trials (i.e. at least 27/30 trials correct). This demonstrates that, as the task progressed, NRT performance did not suffer because of possibly increasing fatigue.

Our key findings are shown in Figure 2, which depicts the percentage of participants in the quiescence and perceptual task groups who demonstrated insight during post-delay testing. Insight was defined as a (i) sudden reduction in the number of digits computed in the solution string, which (ii) should be coupled with a steep decrease in the time that it takes participants to correctly respond to trials (see Supplementary Information). We found a significant main effect of group in the percentage of participants who showed evidence of insight during testing (Fishers exact test p =

.012). This effect emerged because those who experienced 10 minutes of awake quiescence between the training and testing phases were *more than twice as likely* to demonstrate insight during testing (15/24 participants = 62.50%) as those who experienced an unrelated perceptual task (7/27 participants= 25.93%). Overall, 22/51 (43.31%) of our participants who completed the testing phase demonstrated insight after their allocated 10-minute delay condition. Prior to the demonstration of insight, all participants in the quiescence and task groups input 7 digits in the solution string. Following the demonstration of insight, participants in the quiescence group input a mean of 0.87 digits (SD = 1.25) and participants in the task group input a mean of 0.57 digits (SD = 1.13). The mean number of digits input following the demonstration of insight did not differ between groups ($F(1,20) = 0.327$, $p = .574$, $\eta\rho^2 = .016$). Importantly, this sudden drop in the number of digits entered in the solution string was coupled with a steep decrease in the time that it took participants to respond to trials (see Supplementary Information).

<<INSERT FIGURE 2 ABOUT HERE>>

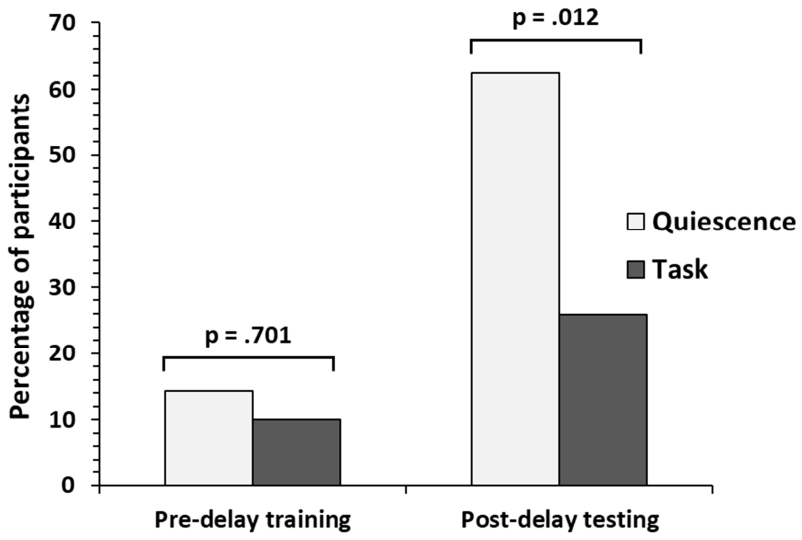

Figure 2. Bar chart showing the percentage of participants in the awake quiescence and perceptual task groups who demonstrated insight (i.e. explicit knowledge of a hidden rule that enabled them to solve the NRT much more quickly than before) during the pre-delay training period or post-delay testing period.

For those who demonstrated insight during the testing phase, there was no between-group difference in the point (trial block) when participants first demonstrated insight (quiescence group: mean = 2.57, SD = 1.45, range = 1-5; task group: mean = 2.57, SD = 1.90, range = 1-6). Only a minority of participants (3 per group) demonstrated insight in the first post-delay testing block of trials. For participants who did not demonstrate insight at any stage, and who completed all 300 post-delay phase NRT trials, there was no significant between-group difference in the time that it took participants to complete testing phase trials ($F(1,30) = 0.072$, $p = .791$, $\eta\rho^2 = .002$; quiescence group: mean = 67.33 minutes, SD = 17.21 minutes; task group: mean = 67.40 minutes, SD = 13.11 minutes).

Discussion

Our results reveal that participants who experienced awake quiescence (quiet rest) for 10 minutes after initial NRT training were more than twice as likely to gain insight into a hidden rule during subsequent NRT trials than participants who played a spot-the-difference game after initial NRT training. This rest-related advantage in the NRT was like that shown previously following an extended sleep (Wagner et al., 2004). Therefore, our finding suggests that a short period of awake quiescence facilitates the gaining of insight, and that sleep is not necessary for this beneficial effect to emerge.

Why was awake quiescence conducive to the development of insight in our study? It has been suggested that taking a break from an ongoing problem can facilitate insight because it diverts the solver's attention from the problem. This is said to release them from the application of a specific strategy, so that a new (possible more efficient) strategy can be applied post-break (Segal, 2004). According to this hypothesis no (conscious or unconscious) insight-related activity occurs during the break, and, as long as the task performed during the break offers a switch in attention from the ongoing problem, the *type* of task performed should not influence subsequent insight (e.g. Segal, 2004). Critically, in our study, participants in both delay condition groups (quiescence and task) experienced a 10-minute break that involved a switch in attention from the NRT, before returning to perform further NRT trials. Therefore, it is unlikely that this 'attention-withdrawal hypothesis' can account for our finding that people who experienced quiescence during the 10-minute delay were more than twice as likely to demonstrate insight as people who engaged in an unrelated perceptual task during the same time. In addition, reduced cognitive fatigue due to rest is unlikely to explain our findings as the spot-the-difference game performed during the task delay is not especially cognitively demanding. Moreover, it is unlikely that fatigue influenced our results more generally because (i) each block of 30 trials was followed by a short break (10 seconds) to reduce fatigue accumulation, and (ii) for those who did not gain insight in the quiescence and task groups, performance was >90% correct even in the 10th block during testing.

Could conscious/intentional thought processes account for the benefit of awake quiescence in our study? It could be argued that our quiescence delay condition might have simply provided a state during which participants could intentionally think about the NRT and thus discover the hidden rule. However, this is unlikely as participants were (i) not aware that there was a hidden rule to solve the NRT more efficiently, and (ii) not informed that they would perform further NRT trials after their allocated 10-minute delay condition. Therefore, our participants had no reason to actively think about the NRT and alternative solutions. Although we cannot rule out the possibility that some participants nonetheless thought about the NRT while resting, it is highly unlikely that they could have discovered the hidden rule intentionally while doing so, because this would require the explicit remembering of at least some of the exact digit sequences presented previously and working through these again mentally. Even if some participant had been able to do so, they would have been expected to demonstrate insight in the first block of the NRT testing phase, i.e. immediately after the delay phase. A small number of participants (N=4) did demonstrate such behaviour in the quiescence group, but this was also the case for the task group (N=3). Thus, it is unlikely that the benefit of awake quiescence could be accounted for by active NRT-related thought. In keeping with this reasoning, research investigating the beneficial effect of quiescence in the retention of new information shows that the rest effect *is not* dependent on intentional thoughts about such information (e.g. Dewar et al., 2014).

A more likely explanation for the benefit of awake quiescence in gaining insight is better consolidation during rest. Specifically, it is possible that newly acquired memory traces pertaining to the NRT were stabilised and reorganised during our 10-minute delay condition 'incubation period'

via consolidation, and especially so during awake quiescence. In line with prior accounts of sleep-related insight (Wagner et al., 2004), this heightened memory reorganisation during awake quiescence may have facilitated the extraction of a hidden rule in the NRT, thereby increasing the chance of gaining of insight. In keeping with this possible consolidation-related explanation, recent work has shown that specific patterns of neural activity during slow wave sleep (SWS) are predictive of whether people will subsequently demonstrate insight in the NRT. This work proposed that these patterns of activity were related to consolidation of new representations during sleep, where a greater magnitude of consolidation-related neural activity resulted in superior reorganisation of memories that facilitated the development of new explicit (insightful) knowledge (Yordanova et al., 2012, 2009). Moreover, some previous research has demonstrated that longer wakeful incubation periods result in an increased likelihood of gaining insight, which is in keeping with the time-dependent nature of consolidation, though findings are mixed (for review see Sio and Ormerod, 2009). In addition, research implicates the involvement of the medial-temporal lobe in performance of the NRT (Darsaud et al., 2011; Rose, Haider, Salari, & Buchel, 2011; Rose et al., 2002; Yordanova et al., 2009). This structure is strongly associated with the consolidation (and neural reactivation) of new memories (Carr et al., 2011; Dewar, Pesallaccia, Cowan, Provinciali, & Della Sala, 2012; Dudai, 2004; Mednick et al., 2011; Tambini et al., 2010), and it is possible that this increased neural activity within the medial temporal lobe could, at least somewhat, reflect consolidation-related activity.

Why might awake quiescence be conducive to the consolidation-related facilitation of insight? Consolidation is proposed to be an opportunistic process that occurs particularly during periods of minimal sensory input and ongoing cognitive engagement, i.e. sleep and awake quiescence (Mednick et al., 2011; Wixted, 2004). This hypothesis is backed up by a wealth of behavioural and neuroscientific research in humans and non-human animals demonstrating that consolidation (Craig, Wolbers, et al., 2016; Craig et al., 2015; Craig, Dewar, et al., 2016; Deuker et al., 2013; Dewar, Alber, et al., 2012; Dewar et al., 2014; Ferrara et al., 2006; Tambini et al., 2010; Wixted, 2004) and neural replay (Carr et al., 2011; Deuker et al., 2013; Gupta, van der Meer, Touretzky, & Redish, 2010; Karlsson & Frank, 2009; Staresina, Alink, Kriegeskorte, & Henson, 2013; Tambini et al., 2010), which is proposed to be a key underlying mechanism of consolidation, occur especially during periods of sleep and awake quiescence.

How might neural replay facilitate the gaining of insight? It is important to note that replay is not restricted to specific or actual experiences (Gupta et al., 2010). For example, spatial memory research in rodents has demonstrated that, following the exploration of a novel route through a spatial environment, memories pertaining to the travelled route are replayed both in the direction in which they were originally travelled (forward) and in a reverse direction, i.e. in a direction in which they were *not originally travelled* (Diba & Buzsáki, 2007; Foster & Wilson, 2006). Moreover, 'replay' patterns for novel routes that were *never directly* travelled are also observed (Derdikman & Moser, 2010; Dragoi & Tonegawa, 2011; Gupta et al., 2010). This 'preplay' is proposed to support the wider integration of individual memory traces into a holistic representation of the spatial environment (Derdikman & Moser, 2010). This resonates with research in humans demonstrating that (i) sleep facilitates the integration of novel concepts into existing memory, from which novel explicit knowledge can be achieved (Gaskell et al., 2014; Lewis & Durrant, 2011; Skaggs & McNaughton, 1996; Tamminen et al., 2010) and (ii) a brief period of awake quiescence following navigation facilitates the integration of new spatial memories into a holistic cognitive (mental) map (Craig, Wolbers, et al., 2016; Craig, Dewar, et al., 2016). In a similar vein, these types of replay during awake quiescence, and indeed sleep, might facilitate the integration of novel information and the extraction of recurring patterns, such as the hidden rule in the NRT.

We note however that although this consolidation/replay hypothesis can account well for the benefit of awake quiescence and sleep in gaining insight, our experimental design does not allow us to rule out an alternative explanation for our finding. Unlike Wagner et al.'s (2004) comparable sleep study, our study did not include a control condition, in which a period of awake quiescence or a

perceptual task, respectively, occurred before any solution attempts on the NRT were made by participants. Therefore, we cannot exclude the possibility that, rather than facilitating better consolidation, awake quiescence provided conditions that induced a more flexible mindset (regardless of prior encoding of the problem representation) that was conducive to detecting a short-cut solution in the NRT. Future work is needed to tease apart these possible explanations

This notwithstanding, irrespective of the specific underpinnings of the benefit of awake quiescence in gaining insight, our findings indicate that a short period of awake quiescence facilitates the gaining of insight, and that sleep is not necessary for this beneficial effect to emerge. Therefore, our findings might explain why some studies have failed to find an overall difference in solution rates following an incubation period comprising an extended period of sleep or wakefulness under strict experimental conditions (e.g. Cai, Mednick, Harrison, Kanady, & Mednick, 2009; Schönauer et al., 2018). Specifically, it is possible that similar insight-related processes, e.g. replay, occur during both sleep and wakefulness, and that if the conditions experienced during wakefulness (e.g. strict conditions of quiet rest as in Cai et al., 2009) facilitate these processes, a similar effect of sleep and wakefulness can be observed.

Indeed, it is noteworthy that the proportion of participants who gained insight in the NRT following 10 minutes of awake quiescence in the current study (62.50%) is comparable to the proportion of participants who gained insight following an extended (~8 hours) period of sleep in previous work (59.1% in Wagner et al. 2004) and greater than the proportion of participants who gained insight following a short (~4 hours) sleep period (25.45% in Yordanova et al. 2008). This might suggest that awake quiescence is equally or indeed more conducive to the underlying mechanisms that support the development of insight, at least in the NRT. However, relative to previous work that has used the NRT to investigate the effect of sleep in developing insight (e.g. Wagner et al., 2004; Yordanova et al., 2009), our study used fewer learning trials (60 trials rather than 90 trials). In addition, the method by which participants entered the 'final solution' digit was different to previous studies. Specifically, in an NRT trial, the solution digit is usually marked by the participant by pressing the 'Enter' key after typing the solution digit. In the current study, participants were required to mark the solution digit by moving the cursor to one of three permanently presented digits (i.e. '1', '4', '9') at the bottom of the computer screen and pressing the mouse key. It is possible that this change in response method promoted the expression of having found the insight solution, by clearly distinguishing the act of entering the final result from the processing of the chain of digits. These between-study methodological differences mean that comparisons between the current data and those of previous studies should be carried out with caution. Moreover, the noted methodological differences may account for some of the between-study differences in the rate of participants who gained insight following sleep and awake quiescence (see above).

Finally, we note that it is questionable whether the NRT is best suited to examine the development of insight problem solving. Specifically, an important aspect in defining insight is the overcoming of a state of impasse by restructuring/decomposing the problem representation, which requires an explicit representation of a currently unreachable problem solution (e.g. Knoblich, Ohlsson, Haider, & Rhenius, 1999; Öllinger, Jones, & Knoblich, 2014). In the NRT, participants are not aware that an alternative, more efficient, solution strategy exist. This makes it difficult to interpret findings in keeping with traditional theories of insight problem solving that are based on studies which have employed well-defined problem-solving tasks, where participants are required to transcend an impasse to discover a solution. Thus, future work should examine whether the beneficial effect of awake quiescence in gaining insight is also observable in more traditional problem-solving tasks.

Conclusion

We provide evidence that the wakeful activities that people engage in immediately after facing a problem affect the probability of gaining insight into a novel solution. Specifically, our findings suggest that people are more likely to gain insight into a novel solution to a problem if they rest briefly after being exposed to the problem than if they engage in a further cognitive task involving ongoing sensory input. Our findings indicate that, at least for the NRT, the facilitation of insight is not restricted to sleep but can be achieved via a brief period of awake quiescence, and possibly states of reduced sensory processing more generally. Thus, contrary to conventional wisdom and theories, when faced with a novel problem we may not always need to 'sleep on it' to develop new explicit knowledge that facilitates more efficient task performance, simply 'resting on it' may be enough. We suggest that our findings might be explained by superior consolidation during awake quiescence, though we cannot rule out all alternative explanations. Future work should use neuroscientific methods to examine the specific neurocognitive mechanisms underlying the development of insight during wakefulness and the benefit of awake quiescence in this process, as well as directly comparing the effects of awake quiescence and sleep on the gaining of insight.

Ethics statement

This research was approved by Heriot-Watt University's School of Social Sciences Psychology Research Ethics Committee (Ref: 2016-272) and all procedures adhered to the appropriate ethical principles for research in humans. All participants were briefed and provided their informed consent in writing prior to their participation.

Author contributions statement

Michael Craig and Michaela Dewar conceptualised the study. Georgina Ottaway contributed toward piloting, task development and data collection. Michael Craig performed data analyses. All authors contributed to writing the paper and approved the paper before submission.

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Additional information

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References

Backhaus, J., & Junghanns, K. (2006). Daytime naps improve procedural motor memory. *Sleep*

Medicine, *7*(6), 508–512.

Cai, D. J., Mednick, S. A., Harrison, E. M., Kanady, J. C., & Mednick, S. C. (2009). REM, not incubation, improves creativity by priming associative networks. *Proceedings of the National Academy of Sciences*, *106*(25), 10130–10134.

Cairney, S. A., Guttesen, A. á. V., El Marj, N., & Staresina, B. P. (2018). Memory Consolidation Is Linked to Spindle-Mediated Information Processing during Sleep. *Current Biology*, *28*(6), 948–954.e4.

Carr, M. F., Jadhav, S. P., & Frank, L. M. (2011). Hippocampal replay in the awake state: a potential substrate for memory consolidation and retrieval. *Nature Neuroscience*, *14*(2), 147–153.

Clemens, Z., Fabó, D., & Halász, P. (2005). Overnight verbal memory retention correlates with the number of sleep spindles. *Neuroscience*, *132*(2), 529–535.

Craig, M., & Dewar, M. (2018). Rest-related consolidation protects the fine detail of new memories. *Scientific Reports*, *8*(1).

Craig, M., Dewar, M., Della Sala, S., & Wolbers, T. (2015). Rest Boosts the Long-term Retention of Spatial Associative and Temporal Order Information. *Hippocampus*, *25*(9), 1017–1027.

Craig, M., Dewar, M., Harris, M. A., Della Sala, S., & Wolbers, T. (2016). Wakeful rest promotes the integration of spatial memories into accurate cognitive maps. *Hippocampus*, *26*(2), 185–193.

Craig, M., Sala, S. D., Dewar, M., Della Sala, S., & Dewar, M. (2014). Autobiographical thinking interferes with episodic memory consolidation. *PLOS ONE*, *9*(4), e93915.

Craig, M., Wolbers, T., Harris, M. A., Hauff, P., Della Sala, S., & Dewar, M. (2016). Comparable Rest-related Promotion of Spatial Memory Consolidation in Younger and Older Adults. *Neurobiology of Aging*, *48*, 143–152.

Darsaud, A., Wagner, U., Balteau, E., Desseilles, M., Sterpenich, V., Vandewalle, G., … Maquet, P. (2011). Neural precursors of delayed insight. *Journal of Cognitive Neuroscience*, *23*(8), 1900–1910.

Debarnot, U., Rossi, M., Faraguna, U., Schwartz, S., & Sebastiani, L. (2017). Sleep does not facilitate insight in older adults. *Neurobiology of Learning and Memory*, *140*, 106–113.

Derdikman, D., & Moser, M.-B. (2010). A dual role for hippocampal replay. *Neuron*, *65*(5), 582–584.

Deuker, L., Olligs, J., Fell, J., Kranz, T. A., Mormann, F., Montag, C., … Axmacher, N. (2013). Memory consolidation by replay of stimulus-specific neural activity. *The Journal of Neuroscience*, *33*(49), 19373–19383.

Dewar, M., Alber, J., Butler, C., Cowan, N., & Della Sala, S. (2012). Brief wakeful resting boosts new memories over the long term. *Psychological Science*, *23*(9), 955–60.

Dewar, M., Alber, J., Cowan, N., & Della Sala, S. (2014). Boosting Long-Term Memory via Wakeful Rest: Intentional Rehearsal Is Not Necessary, Consolidation Is Sufficient. *PLoS ONE*, *9*(10), e109542.

Dewar, M., Cowan, N., & Della Sala, S. (2007). Forgetting due to retroactive interference: a fusion of Müller and Pilzecker's (1900) early insights into everyday forgetting and recent research on anterograde amnesia. *Cortex*, *43*(5), 616–634.

Dewar, M., Pesallaccia, M., Cowan, N., Provinciali, L., & Della Sala, S. (2012). Insights into spared memory capacity in amnestic MCI and Alzheimer's Disease via minimal interference. *Brain and*

Cognition, *78*(3), 189–199.

Diba, K., & Buzsáki, G. (2007). Forward and reverse hippocampal place-cell sequences during ripples. *Nature Neuroscience*, *10*(10), 1241–2.

Dodds, R. A., Ward, T. B., & Smith, S. M. (2004). A review of experimental research on incubation in problem solving and creativity. *Review Literature And Arts Of The Americas*, 1–51.

Dragoi, G., & Tonegawa, S. (2011). Preplay of future place cell sequences by hippocampal cellular assemblies. *Nature*, *469*(7330), 397–401.

Dudai, Y. (2004). The neurobiology of consolidations, or, how stable is the engram? *Annual Review of Psychology*, *55*, 51–86.

Dudai, Y. (2012). The restless engram: consolidations never end. *Annual Review of Neuroscience*, *35*(March), 227–247.

Dumay, N., & Gaskell, M. G. (2007). Sleep-associated changes in the mental representation of spoken words: Research report. *Psychological Science*, *18*, 35–39.

Ego-Stengel, V., & Wilson, M. A. (2011). Disruption of ripple-associated hippocampal activity during rest impairs spatial learning in the rat. *Hippocampus*, *20*(1), 1–10.

Ferrara, M., Iaria, G., De Gennaro, L., Guariglia, C., Curcio, G., Tempesta, D., & Bertini, M. (2006). The role of sleep in the consolidation of route learning in humans: a behavioural study. *Brain Research Bulletin*, *71*(1–3), 4–9.

Ferrara, M., Iaria, G., Tempesta, D., Curcio, G., Moroni, F., Marzano, C., … Pacitti, C. (2008). Sleep to find your way: the role of sleep in the consolidation of memory for navigation in humans. *Hippocampus*, *18*(8), 844–851.

Foster, D. J., & Wilson, M. A. (2006). Reverse replay of behavioural sequences in hippocampal place cells during the awake state. *Nature*, *440*(7084), 680–683.

Gaskell, M. G., Warker, J., Lindsay, S., Frost, R., Guest, J., Snowdon, R., & Stackhouse, A. (2014). Sleep Underpins the Plasticity of Language Production. *Psychological Science*, *25*(June), 1457–1465.

Gupta, A. S., van der Meer, M. A. A., Touretzky, D. S., & Redish, A. D. (2010). Hippocampal replay is not a simple function of experience. *Neuron*, *65*(5), 695–705.

Hélie, S., & Sun, R. (2010). *Incubation, insight, and creative problem solving: A unified theory and a connectionist model. Psychological Review* (Vol. 117).

Ji, D., & Wilson, M. A. (2007). Coordinated memory replay in the visual cortex and hippocampus during sleep. *Nature Neuroscience*, *10*(1), 100–107.

Karlsson, M. P., & Frank, L. M. (2009). Awake replay of remote experiences in the hippocampus. *Nature Neuroscience*, *12*(7), 913–918.

Knoblich, G., Ohlsson, S., Haider, H., & Rhenius, D. (1999). Constraint Relaxation and Chunk Decomposition in Insight Problem Solving. *Journal of Experimental Psychology: Learning Memory and Cognition*, *25*(6), 1534–1555.

Lahl, O., Wispel, C., Willigens, B., & Pietrowsky, R. (2008). An ultra short episode of sleep is sufficient to promote declarative memory performance. *Journal of Sleep Research*, *17*(1), 3–10.

Lewis, P. A., & Durrant, S. J. (2011). Overlapping memory replay during sleep builds cognitive schemata. *Trends in Cognitive Sciences*, *15*(8), 343–51.

Mednick, S. C., Cai, D. J., Shuman, T., Anagnostaras, S., & Wixted, J. T. (2011). An opportunistic theory of cellular and systems consolidation. *Trends in Neurosciences*, *34*(10), 504–514.

Öllinger, M., Jones, G., & Knoblich, G. (2014). The dynamics of search, impasse, and representational change provide a coherent explanation of difficulty in the nine-dot problem. *Psychological Research*, *78*(2), 266–275.

Peirce, J. W. (2008). Generating Stimuli for Neuroscience Using PsychoPy. *Frontiers in Neuroinformatics*, *2*(January), 10.

Peyrache, A., Khamassi, M., Benchenane, K., Wiener, S. I., & Battaglia, F. P. (2009). Replay of rule-learning related neural patterns in the prefrontal cortex during sleep. *Nature Neuroscience*, *12*(7), 919–926.

Posner, M. I. (1973). *Cognition: An Introduction*. (S. Foresman, Ed.). Glenview, IL.

Ramadan, W., Eschenko, O., & Sara, S. J. (2009). Hippocampal sharp wave/ripples during sleep for consolidation of associative memory. *PloS ONE*, *4*(8), e6697.

Rose, M., Haider, H., Salari, N., & Buchel, C. (2011). Functional Dissociation of Hippocampal Mechanism during Implicit Learning Based on the Domain of Associations. *Journal of Neuroscience*, *31*(39), 13739–13745.

Rose, M., Haider, H., Weiller, C., & Büchel, C. (2002). The Role of Medial Temporal Lobe Structures in Implicit Learning. *Neuron*, *36*(6), 1221–1231.

Schönauer, M., Alizadeh, S., Jamalabadi, H., Abraham, A., Pawlizki, A., & Gais, S. (2017). Decoding material-specific memory reprocessing during sleep in humans. *Nature Communications*, *8*(May).

Schönauer, M., Brodt, S., Pöhlchen, D., Breßmer, A., Danek, A. H., & Gais, S. (2018). Sleep Does Not Promote Solving Classical Insight Problems and Magic Tricks. *Frontiers in Human Neuroscience*, *12*(February), 1–11.

Segal, E. (2004). Incubation in Insight Problem Solving. *Creativity Research Journal*, *16*(1), 141–148.

Sio, U. N., & Ormerod, T. C. (2009). Does incubation enhance problem-solving? A meta-analytic review. *Psychological Bulletin*, *135*, 94–120.

Skaggs, W. E., & McNaughton, B. L. (1996). Replay of neuronal firing sequences in rat hippocampus during sleep following spatial experience. *Science (New York, N.Y.)*, *271*(5257), 1870–1873.

Smith, S. M., & Blankenship, S. E. (1989). Incubation effects. *Bulletin of the Psychonomic Society*, *27*(4), 311–314.

Staresina, B. P., Alink, A., Kriegeskorte, N., & Henson, R. N. (2013). Awake reactivation predicts memory in humans. *Proceedings of the National Academy of Sciences*, *110*(52), 21159–21164.

Tambini, A., Ketz, N., & Davachi, L. (2010). Enhanced brain correlations during rest are related to memory for recent experiences. *Neuron*, *65*(2), 280–290.

Tamminen, J., Payne, J. D., Stickgold, R., Wamsley, E. J., & Gaskell, M. G. (2010). Sleep spindle activity is associated with the integration of new memories and existing knowledge. *The Journal of Neuroscience*, *30*(43), 14356–14360.

Tan, T., Zou, H., Chen, C., & Luo, J. (2015). Mind Wandering and the Incubation Effect in Insight Problem Solving. *Creativity Research Journal*, *27*(4), 375–382.

Verleger, R., Rose, M., Wagner, U., Yordanova, J., Kolev, V., Haider, H., … Büchel, C. (2013). Insights

into sleep's role for insight: Studies with the number reduction task. *Neuron*, *36*(6), 1221–1231.

Wagner, U., Gais, S., Haider, H., Verleger, R., & Born, J. (2004). Sleep inspires insight. *Nature*, *427*(6972), 352–5.

Walker, M. P., Brakefield, T., Seidman, J., Morgan, A., Hobson, J. A., & Stickgold, R. (2003). Sleep and the time course of motor skill learning. *Learning & Memory*, *10*(4), 275–284.

Wamsley, E. J. (2014). Dreaming and offline memory consolidation. *Current Neurology and Neuroscience Reports*, *14*(3), 433.

Wamsley, E. J., Tucker, M. A., Payne, J. D., & Stickgold, R. (2010). A brief nap is beneficial for human route-learning: The role of navigation experience and EEG spectral power. *Learning & Memory*, *17*(7), 332–336.

Warker, J. A., & Dell, G. S. (2006). Speech errors reflect newly learned phonotactic constraints. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *32*(2), 387–98.

Wilson, M. a, & McNaughton, B. L. (1994). Reactivation of Hippocampus Ensemble Memories During SLeep. *Science*, *5*(14), 14–17.

Wixted, J. T. (2004). The psychology and neuroscience of forgetting. *Annual Review of Psychology*, *55*, 235–269.

Yordanova, J., Kolev, V., Verleger, R., Bataghva, Z., Born, J., & Wagner, U. (2008). Shifting from implicit to explicit knowledge: Different roles of early-and late-night sleep. *Learning & Memory*, *15*(7), 508.

Yordanova, J., Kolev, V., Wagner, U., Born, J., & Verleger, R. (2012). Increased Alpha (8–12 Hz) Activity during Slow Wave Sleep as a Marker for the Transition from Implicit Knowledge to Explicit Insight. *Journal of Cognitive Neuroscience*, *24*(1), 119–132.

Yordanova, J., Kolev, V., Wagner, U., & Verleger, R. (2009). Covert reorganization of implicit task representations by slow wave sleep. *PLoS ONE*, *4*(5).